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Review Paper

Industrial Symbiosis and Eco-Industrial Parks in the Era of ESG and Decarbonization: Assessment Methods, Regional Scaling, and Sectoral Evidence from 2000-2026

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ABSTRACT

Industrial symbiosis (IS) and eco-industrial parks (EIPs) have evolved from descriptive accounts of by-product exchange into a more demanding field centered on quantified performance, regional coordination, and environmental, social, and governance (ESG) accountability. Building on the attached review base and newly added abstract corpus, this article synthesizes the field using only the provided materials, spanning foundational conceptual studies, bibliometric and systematic reviews, case-based life cycle assessment (LCA), hybrid and consequential models, network and regional planning studies, and recent work on uncertainty, optimization, and ESG-oriented decision support. Three findings dominate. First, evidence for environmental improvement is strong, but its magnitude depends on baselines, allocation, transport, substitution, and market assumptions. Second, the field is moving from isolated exchange evaluation toward multi-level assessment linking firm, flow, park, and regional outcomes. Third, the newest studies show that future EIPs will be judged not only by waste diversion and carbon savings, but also by resilience, governance quality, welfare, community legitimacy, and transparent investment prioritization. The review therefore proposes an updated framework connecting industrial ecology metrics with regional transition management and ESG governance, and argues that future research should focus less on whether symbiosis can work and more on when, for whom, at what scale, and under which governance arrangements it remains environmentally robust, socially legitimate, and economically actionable.

***Keywords*: industrial symbiosis; eco-industrial parks; life cycle assessment; ESG; circular economy; decarbonization; regional industrial networks**

1. INTRODUCTION

Industrial symbiosis has long been presented as one of the most concrete operational expressions of industrial ecology because it turns the abstract idea of circularity into observable exchanges of materials, energy, water, services, and knowledge among firms. The early literature established the conceptual foundation by defining IS as a collaborative strategy through which traditionally separate industries improve resource efficiency through mutually beneficial linkages, while later reviews and bibliometric studies showed how the field expanded from emblematic cases toward diversified analytical, regional, and policy research agendas (Chertow, 2000; Yu et al., 2014; Zhang et al., 2015; Rahman et al., 2016; Yeo et al., 2019; Neves et al., 2020; Vahidzadeh & Bertanza, 2022).

At the same time, the maturation of the field has made evaluation more demanding. In the earlier phase of research, it was often enough to demonstrate that a by-product exchange or energy cascade reduced waste disposal, displaced virgin inputs, or lowered selected emissions. However, the accumulated literature now shows that these claims are not self-validating. Environmental benefit depends on what baseline is chosen, how credits are allocated, whether transport burdens erode gains, how substitution ratios are modeled, and whether the assessment captures effects at the single-firm, network, or regional level (Ardente et al., 2010; Mattila et al., 2010; Mattila et al., 2012; Martin et al., 2015; Aissani et al., 2019; Kerdlap et al., 2020a, 2020b; Ruini et al., 2025). This is precisely why an updated review is needed: the contemporary literature is no longer simply about whether symbiosis is desirable, but about how to measure its real performance with enough rigor to support planning, investment, and governance.

The attached source base is especially valuable because it captures this transition. It contains foundational conceptual works, systematic reviews, and bibliometric analyses; numerous life cycle assessment studies from cement, steel, chemicals, forest products, bioenergy, waste management, and agri-food systems; and a growing body of research on modeling, indicators, social-network analysis, regional planning, and uncertainty. Importantly, the most recent additions move the discussion toward ESG, multilevel decision support, supply-chain resilience, and more explicit questions of regional governance and strategic prioritization (Carissimi et al., 2024; Kerdlap et al., 2024; Lessard et al., 2024; Barrau et al., 2024; Domini et al., 2025; Ruini et al., 2025; Anelli et al., 2026).

A central argument of this article is that the field has entered an integrative phase. Early scholarship focused on identifying symbioses, later work concentrated on proving environmental benefits in particular cases, and recent studies increasingly embed those benefits in network analysis, planning models, decision support, and ESG-oriented governance (Chertow, 2000; Hashimoto et al., 2010; Sokka et al., 2011; Eckelman & Chertow, 2013; Yu et al., 2015; Felicio et al., 2016; Demartini et al., 2022; Kerdlap et al., 2024; Barrau et al., 2024; Anelli et al., 2026). A contemporary review must therefore clarify methodological tensions, scalability limits, and governance conditions rather than simply repeat generic claims of circularity.

2. Review basis and synthesis logic

This article is based exclusively on the attached review material and the attached RIS abstract dataset. The corpus covers 2000–2026 and includes conceptual papers, bibliometric and systematic reviews, methodological articles, case-based LCA studies, social-network and regional analyses, and emerging work on ESG and multi-criteria optimization. Because the corpus is abstract-based for most entries, the purpose here is not to reproduce every technical specification of the original studies, but to construct a high-integrity synthesis of the research trajectories, core findings, recurring methodological choices, and unresolved debates represented in the provided materials (Yu et al., 2014; Yeo et al., 2019; Kerdlap et al., 2020a, 2020b; Neves et al., 2020; Demartini et al., 2022; Vahidzadeh & Bertanza, 2022).

The synthesis logic follows three principles. First, studies are interpreted by analytical role rather than merely by chronology. Some papers are foundational because they define concepts or map the field; others are methodological because they refine impact accounting; others are empirical because they validate sector-specific symbioses; and a final set is strategic because it addresses scaling, planning, or governance. This role-based reading matters because the most cited or earliest papers do not automatically resolve the most recent methodological questions. For instance, foundational taxonomies remain indispensable, but they do not answer current concerns about uncertainty in consequential LCA or how to rank investment options across EIPs (Chertow, 2000; Mattila et al., 2012; Lessard et al., 2024; Anelli et al., 2026).

Third, the review reads recent literature as evidence of field recomposition. The newer studies do not simply add more cases. They reorganize the evaluative architecture of IS research by linking life-cycle methods with cost analysis, optimization, social-network analysis, regional planning, circular supply-chain thinking, and ESG governance (Vahidzadeh et al., 2021; Demartini et al., 2022; Carissimi et al., 2024; Kerdlap et al., 2024; Domini et al., 2025; Anelli et al., 2026). This is the basis for the interpretive claim that the field is moving from proof-of-concept case studies to decision-oriented transition infrastructure.

Table 1. Milestones in methods for evaluating industrial symbiosis and eco-industrial parks

Analytical focus	Typical method or lens	Main contribution to the field	Main caution or limitation highlighted in the corpus	Ref.
Foundational conceptualization	Taxonomy and industrial ecology framing	Established IS as collaborative exchange of materials, energy, water, and services; clarified the field's boundaries	Conceptual richness initially exceeded standardized performance measurement	Chertow (2000)
Research evolution mapping	Bibliometric and review synthesis	Showed rapid diversification of themes, methods, and geographies in IS research	Growth of literature increased fragmentation of terminology and metrics	Yu et al. (2014); Zhang et al. (2015)
Strategy selection among industrial ecology options	LCA-informed comparison of alternatives	Positioned LCA as a decision aid rather than a mere reporting tool	Results depend heavily on scenario construction and comparison logic	Ardente et al. (2010)
Total environmental accounting	Process, hybrid, and input–output LCA comparison	Demonstrated that different LCA architectures yield different system-level estimates	Method choice can significantly alter estimated benefits	Mattila et al. (2010)
Methodological consolidation	LCA guidance for IS	Clarified functional units, system boundaries, and reference systems for IS studies	No single default reference system is universally appropriate	Mattila et al. (2012)
Benefit distribution	Firm-level credit allocation	Moved from network-level gains to distribution of benefits among actors	Allocation may alter incentives and perceptions of fairness	Martin et al. (2015); Ruini et al. (2025)
Indicatorization of EIPs	Dynamic indicator systems	Shifted evaluation toward park management and operational monitoring	Indicator sets risk simplification if disconnected from causality	Felicio et al. (2016)
Critical reflection on baselines	Review of reference scenarios	Showed that avoided-burden claims are highly reference-dependent	Weak baselines can overstate symbiosis benefits	Aissani et al. (2019)
Multi-level environmental accounting	Matrix-based multi-level LCA	Connected flow-, entity-, and network-level impacts in one model	Data intensity rises with scale and level of detail	Kerdlap et al. (2020)

Integrated environmental-economic evaluation	Multi-level LCA + LCC	Enabled simultaneous environmental and economic analysis of IS networks	Requires harmonized datasets and more complex modeling assumptions	Kerdlap et al. (2024)
Comparative product communication	EPD and footprint comparison	Highlighted implications of methodological inconsistency for comparability	Different rules can produce different environmental scores for similar outputs	Durão et al. (2020); Konradsen et al. (2024)
Robust policy-oriented prioritization	ESG + two-phase goal-programming optimization	Linked gap assessment to actionable improvement portfolios for EIPs	Social and governance dimensions remain harder to operationalize than environmental ones	Anelli et al. (2026)

3. From taxonomy to transition infrastructure: how the field evolved

The early literature framed IS primarily as a relational and spatial phenomenon. The central insight was that industrial systems could mimic some features of natural ecosystems by circulating resources rather than linearly discarding them. In this framing, the key research task was to identify exchange patterns, classify symbiotic types, and explain why some industrial clusters developed dense synergies while others did not (Chertow, 2000; Zhang et al., 2015; Rahman et al., 2016). This was a necessary starting point, but it also left a legacy problem: the field became rich in narratives of possibility before it became equally strong in standardized evidence of performance.

Bibliometric and review studies show how quickly this imbalance became visible. As publication volume increased, the literature diversified into distinct but overlapping streams: conceptual development, case-based environmental assessment, implementation barriers, policy instruments, tools and platforms, and regional planning (Yu et al., 2014; Rahman et al., 2016; Yeo et al., 2019; Neves et al., 2020; Demartini et al., 2022). This diversification was productive, but it also fragmented the field. Different studies evaluated different objects—single exchanges, firm pairs, eco-industrial parks, urban systems, or regional networks—using different metrics and baseline assumptions. The consequence is that “industrial symbiosis works” became an overly broad statement that obscures major differences in what exactly was measured and for whom the benefits accrued (Martin et al., 2015; Wadström et al., 2021; Arce Bastias et al., 2023; Ruini et al., 2025).

The next important shift was from descriptive taxonomies to quantified environmental validation. A series of LCA studies demonstrated that symbiosis could reduce carbon emissions, energy use, and waste burdens in sectors such as cement, forestry, municipal solid waste, sludge treatment, and industrial parks (Hashimoto et al., 2010; Geng et al., 2010; Liu et al., 2011; Sokka et al., 2011; Eckelman & Chertow, 2013; Yu et al., 2015). These studies were pivotal because they transformed industrial symbiosis from an appealing systems metaphor into an evaluable strategy. At the same time, they revealed that benefits are not automatic. In several cases, gains depended on substitution ratios, local infrastructure, emission profiles of displaced products, and the ability to avoid burdensome transport or preprocessing (Liu et al., 2011; Martin, 2015; Marcinkowski, 2019; Martin, 2020).

Recent reviews and modeling papers suggest that the field is again changing its center of gravity. The most advanced studies no longer ask only whether a particular exchange saves emissions, but how environmental and economic effects are distributed across network members, how symbioses can be evaluated at multiple scales, and what modeling structures best support planning (Kerdlap et al., 2020a, 2020b; Haq et al., 2021; Wadström et al., 2021; Demartini et al., 2022; Kerdlap et al., 2024; Anelli et al., 2026). Under this view, EIPs are managed transition platforms requiring tools that compare intervention pathways, expose trade-offs, and prioritize action under real constraints.

The latest contribution in the attached set—the 2026 ESG-oriented comparison of Envipark and Kalundborg—captures this transition particularly well. Rather than treating EIPs as environments where exchanges merely happen, it treats them as strategic infrastructures that can be benchmarked against regulatory and best-practice targets and then optimized through portfolios of improvement measures (Anelli et al., 2026). This shifts the evaluative logic from "What benefits did the existing symbiosis create?" to "What is the gap between current and desired performance, and which bundle of actions closes that gap most effectively?" That is a qualitatively different research question and one that aligns closely with the planning needs of top-tier sustainability governance.

4. The methodological core: LCA, baselines, allocation, and uncertainty

The methodological backbone of the corpus is clearly life cycle assessment. LCA became dominant in IS research because it is uniquely suited to tracking both direct and indirect environmental effects across linked production systems. It offers a structured way to account for substitutions, avoided burdens, transportation, preprocessing, and emissions that occur outside the immediate site of exchange. Studies across multiple sectors use LCA to test whether symbiotic use of secondary materials or surplus energy actually improves overall environmental performance relative to conventional alternatives (Ardente et al., 2010; Liu et al., 2011; Sokka et al., 2011; Eckelman & Chertow, 2013; Daddi et al., 2017; Zhang et al., 2017; Wang et al., 2019). The collective message is clear: LCA remains the most mature common language for environmental evaluation in this field.

Yet the same literature also shows that LCA is not a turnkey solution. One of the most persistent methodological issues is the choice of reference system. Aissani et al. (2019) explicitly identify reference-scenario construction as a critical source of variation in IS studies, while earlier methodological work had already shown that conclusions change when analysts compare different counterfactuals, such as landfilling, virgin production, conventional waste management, or alternative recycling routes (Mattila et al., 2012; Martin et al., 2015). In practical terms, this means that reported environmental gains are only as credible as the baseline against which the symbiosis is measured. A poorly justified reference system can make a modest exchange look transformative or hide an otherwise meaningful intervention.

A second issue concerns system boundaries and scale. Process-based LCAs can capture detailed exchange mechanisms but may omit upstream and economy-wide interactions, whereas hybrid and input–output approaches can broaden the accounting frame at the cost of increased aggregation or less technological specificity (Mattila et al., 2010; Kerdlap et al., 2020a, 2020b). This trade-off has become more important as the field moves from single exchanges to wider networks. What is environmentally beneficial at the dyadic level may look different when assessed at the network or regional scale, especially if expansion of a symbiotic chain changes transport demand, market substitution patterns, or the generation of intermediate residues (Martin & Harris, 2018; Vahidzadeh et al., 2021; Barrau et al., 2024; Domini et al., 2025).

A third methodological tension concerns allocation. Industrial symbiosis often creates benefits that are jointly produced by multiple actors. If a waste stream becomes a substitute input for another firm, or a shared heat infrastructure reduces emissions for several users, how should the environmental credit be distributed? Martin et al. (2015) addressed this directly by proposing an approach for assessing the environmental performance of IS while distributing credits among participating firms, thereby shifting attention from total network benefit to actor-specific outcomes. Ruini et al. (2025) revisit this question and argue that allocation remains a live issue as IS becomes more central to climate and circularity agendas. This debate is not merely technical. Allocation rules shape perceived fairness, business incentives, partnership stability, and the legitimacy of corporate sustainability claims.

A fourth issue is the difference between attributional and consequential reasoning. Many studies in the corpus implicitly or explicitly rely on avoided-burden logic, but recent work underscores that market-mediated consequences and uncertainty are too often underexplored. Lessard et al. (2024), for instance, assess the robustness of consequential LCA in a cement symbiosis context and show that marginal effects and uncertainty can materially affect conclusions. Their contribution is important because it elevates a problem that has often been acknowledged but insufficiently operationalized in IS literature: interventions that look favorable under static assumptions may be less certain once broader economic responses are considered. For top-tier review purposes, this means the literature can no longer be credibly summarized as if all LCA results were commensurate.

The methodological trajectory also includes integration with economic and optimization models. The review by Kerdlap et al. (2020) and the later UM3-LCE3-ISN method (Kerdlap et al., 2024) show that researchers are moving toward models that can simultaneously represent environmental and economic outcomes at multiple levels of network organization. This is a major advance because it helps bridge the common gap between environmentally optimal and managerially actionable symbiosis options. Similarly, Wang et al. (2022) combine hybrid LCA with multiobjective optimization for fly-ash utilization, and Xue et al. (2022) combine material flow analysis, LCA, and a conservation supply curve to assess technology portfolios in the iron and steel sector. These studies illustrate a broader shift from retrospective environmental accounting toward design-oriented decision support.

Taken together, the literature suggests that the methodological frontier is not simply "more LCA." Rather, it is better-specified LCA embedded in transparent baseline construction, explicit allocation logic, uncertainty analysis, multi-level accounting, and integration with cost and planning models (Aissani et al., 2019; Kerdlap et al., 2020a, 2020b; Demartini et al., 2022; Kerdlap et al., 2024; Lessard et al., 2024; Ruini et al., 2025). This is one of the strongest messages emerging from the updated corpus: environmental quantification remains essential, but it must now be connected to decision quality.

Table 2. Representative sectoral evidence on environmental performance and design implications

Sector or system	**Symbiotic exchange or intervention**	**Main findings reported in the literature**	**Strategic implication for practice**	**Ref.**
Cement production	Material substitution and industrial co-processing	Significant CO2 reduction potential, but magnitude depends on substitution assumptions and process context	Cement remains a priority host sector for scalable symbiosis, but robust baselines are essential	Hashimoto et al. (2010); Ammenberg et al. (2015); Capucha et al. (2023); Lessard et al. (2024); Liao et al. (2024)
Municipal solid waste and urban systems	Urban–industrial integration and waste valorization	Symbiosis can improve waste management and lower impacts relative to conventional handling	Urban infrastructure capacity and governance coordination are decisive	Geng et al. (2010); Dong et al. (2014); Dong et al. (2017); Chertow et al. (2019); Wang et al. (2022)

Sludge and used oil recovery	Energy recovery and fuel substitution	Environmental improvements are achievable, but pollutant trade-offs and optimal substitution ratios matter	Design should target optimal operating windows rather than maximum substitution by default	Liu et al. (2011)
Forest, pulp, and lignin systems	Cascading use of side streams and bioenergy integration	Strong environmental advantages often emerge when side streams replace more burdensome products or fuels	Bioeconomy symbiosis is promising, but co-product choices affect final performance	Sokka et al. (2011); Hildebrandt et al. (2019); Secchi et al. (2019); Simões et al. (2024)
Biofuel and sugar systems	Shared energy systems and co-generation	Cogeneration and networked resource use can improve the profile of bio-based products	Symbiosis should be analyzed as part of integrated industrial complexes, not isolated product chains	Martin (2015); Arcentales-Bastidas et al. (2022)
Steel and slag valorization	Slag reuse and symbiotic technologies	Significant emission and energy-reduction potential, especially when technology portfolios are screened systematically	Best available symbiotic technologies can support sectoral decarbonization strategies	Renzulli et al. (2016); Xue et al. (2022); Gobetti et al. (2024)
Construction materials	Incorporation of secondary residues into products	Several studies show meaningful environmental gains from secondary inputs in concrete, wall blocks, and facades	Construction is a major demand sink for secondary materials, but comparability rules matter	Di Maria et al. (2018); Hossain et al. (2021); Vitale et al. (2021); Ali et al. (2020); Konradsen et al. (2024)
Agro-food and aquaculture systems	Food-to-food and biomass residue synergies	Circular resource cascades can reduce burdens when logistics and end-of-life pathways are well aligned	Localized industrial metabolism can be extended to food and agri-systems	Strazza et al. (2015); Zhang et al. (2021); Rodrigues Viana et al. (2023); Ansanelli et al. (2023)
Industry-wide and regional waste management	Cross-sector symbiosis beyond single parks	LCA suggests substantial untapped potential when sectoral waste streams are pooled and matched regionally	Regional screening tools are necessary before infrastructure investment	Paulu et al. (2022); Barrau et al. (2024); Domini et al. (2025)

5. What the case evidence actually shows: strong promise, conditional outcomes

The case-based literature provides persuasive evidence that industrial symbiosis can improve environmental performance in a wide range of sectors. In cement systems, symbiosis has repeatedly been linked to reductions in carbon emissions and raw material demand through substitution and co-processing pathways (Hashimoto et al., 2010; Ammenberg et al., 2015; Capucha et al., 2023; Lessard et al., 2024; Liao et al., 2024). In waste and urban systems, studies show that integrating municipal waste flows with industrial users can improve both disposal outcomes and broader system efficiency (Geng et al., 2010; Dong et al., 2014; Dong et al., 2017; Wang et al., 2022). In forest, biofuel, and agri-food contexts, side streams such as lignin, residues, and surplus biomass can be turned into energy, feed, or material inputs with significant life-cycle benefits when the network is well designed (Sokka et al., 2011; Strazza et al., 2015; Hildebrandt et al., 2019; Secchi et al., 2019; Arcentales-Bastidas et al., 2022; Rodrigues Viana et al., 2023).

But the literature is equally clear that these benefits are contingent, not universal. One of the most instructive examples is the role of transport distance. Marcinkowski (2019) demonstrates that the environmental viability of a symbiotic exchange has spatial limits and introduces the idea of critical distance. This is a powerful corrective to overly generalized circular-economy claims. A material that performs well as a substitute at short range may lose its advantage when moved over longer distances or when a different transport mode is required. The implication is that proximity remains a major structural determinant of symbiosis performance, even in a period of digital matchmaking and platform-based exchange facilitation (Yeo et al., 2019; Vahidzadeh et al., 2021; Domini et al., 2025).

The literature also shows that "waste valorization" is too blunt a category. Different secondary materials behave very differently in environmental terms. For instance, sludge co-combustion may reduce some burdens while increasing others such as acidifying emissions or heavy-metal-related concerns, depending on the operating configuration and substitute ratio (Liu et al., 2011). Likewise, the use of waste glass, photovoltaic residues, stainless steel slag, CFRP waste, coffee silverskin, or paper and pulp residues in new products can be environmentally attractive, but the magnitude and distribution of benefits differ across application pathways, processing requirements, and displaced materials (Blengini et al., 2012; Ilias et al., 2018; Di Maria et al., 2018; Vitale et al., 2021; Ansanelli et al., 2023; Simões et al., 2024). The field has therefore matured beyond generic claims that "using waste is better." The better question is which secondary stream, in which host process, under which market substitution assumptions, delivers the most robust system-wide gain.

Another strong finding is that sectoral host capacity matters. Construction and cement repeatedly emerge as strategically important symbiosis destinations because they can absorb large volumes of secondary materials and often yield meaningful avoided burdens when these materials displace carbon-intensive conventional inputs (Ammenberg et al., 2015; Di Maria et al., 2018; Hossain et al., 2021; Capucha et al., 2023; Liao et al., 2024). Steel and iron systems also show considerable potential, particularly when multiple technologies are screened at portfolio scale rather than one by one (Renzulli et al., 2016; Xue et al., 2022; Gobetti et al., 2024). By contrast, some sectors offer smaller but still strategically relevant opportunities when symbiosis improves local circularity, waste handling, or supply resilience rather than delivering dramatic carbon reductions alone (Sharib & Halog, 2017; Martin et al., 2022; Carissimi et al., 2024).

Case studies also reveal an important difference between network emergence and network optimization. Some articles assess existing symbioses, while others prospect future exchanges or compare alternative pathways. Prospecting studies are especially useful because they reveal that not all technically feasible exchanges are environmentally or strategically worthwhile (Martin & Harris, 2018; Chertow et al., 2019; Neves et al., 2019). The strongest contemporary studies therefore combine environmental quantification with screening or optimization logic so that the literature informs design, not only post hoc evaluation (Xue et al., 2022; Wang et al., 2022; Kerdlap et al., 2024; Anelli et al., 2026).

What emerges overall is a more disciplined understanding of "evidence." The field can reasonably claim that industrial symbiosis often improves environmental performance, but only under a conditional formula: when the reference system is properly constructed, transport and preprocessing do not dominate the burden profile, the substitute genuinely displaces a more impactful alternative, and the analysis captures relevant network-level effects (Mattila et al., 2012; Aissani et al., 2019; Marcinkowski, 2019; Lessard et al., 2024). This conditional formula is not a weakness. On the contrary, it is a sign of methodological maturity. Top-tier review scholarship should make that conditionality explicit rather than flattening the literature into a uniformly celebratory narrative.

6. Networks, regions, and the problem of scale

One of the most important developments in the updated corpus is the move from site-bounded symbiosis to regional network thinking. Early iconic examples encouraged the assumption that industrial parks were the primary locus of IS because geographic proximity made exchanges feasible and because park boundaries provided a manageable governance unit. That logic still matters, but the literature now shows that the real analytical challenge lies in understanding how synergies scale, how they interact with urban and regional infrastructures, and where the effective system boundary should be drawn (Chertow et al., 2019; Vahidzadeh et al., 2021; Vahidzadeh & Bertanza, 2022; Barrau et al., 2024; Domini et al., 2025).

Social-network analysis has become one important tool in this regard. Reviews and regional case studies use SNA to reveal how network density, centrality, and structural positioning influence the diffusion and stability of symbioses (Vahidzadeh et al., 2021; Domini et al., 2025). This matters because environmental potential alone does not create exchanges. Firms must recognize opportunities, trust partners, coordinate logistics, and often commit to long-term infrastructural arrangements. The structure of the network therefore shapes both the emergence of synergies and the resilience of those synergies under market or regulatory change.

Regional analyses also broaden the meaning of capacity. Symbiosis potential is constrained not only by the availability of residual streams, but also by transport systems, treatment facilities, industrial siting, utility networks, and planning-compatible land use (Chertow et al., 2019; Barrau et al., 2024; Domini et al., 2025). Industrial symbiosis should therefore be evaluated as part of territorial metabolism rather than merely interfirm exchange.

This regional turn has implications for measurement. Once the unit of analysis shifts from a single exchange or park to a wider region, conventional case-based LCA may be insufficient on its own. Multi-level methods become more attractive because they can represent entity-level, flow-level, network-level, and sometimes territorial effects in a connected framework (Kerdlap et al., 2020a, 2020b; Kerdlap et al., 2024). Hybrid approaches and broader structural analyses also gain value because regional symbiosis often involves mixed infrastructures, multiple sectors, and indirect interactions that are difficult to capture with narrowly bounded process models (Mattila et al., 2010; Barrau et al., 2024).

At the same time, regional scaling introduces new risks. One risk is overestimating potential by aggregating waste streams without adequately considering quality constraints, timing mismatches, market competition, or transport burdens. Another is conflating technical potential with actionable potential. Several review and barrier studies note that implementation hinges on governance, information exchange, investment confidence, legal clarity, and coordination mechanisms, not only material compatibility (Rahman et al., 2016; Yeo et al., 2019; Neves et al., 2019; Demartini et al., 2022). This means that regional potential maps and network analyses should be treated as strategic filters, not as direct forecasts of realized symbiosis.

The relationship between regional scaling and decarbonization is especially significant. When policy agendas demand deep reductions in material throughput and emissions, the comparative value of symbiosis shifts. It is no longer enough to valorize isolated waste streams opportunistically. Regions need to know which clusters of exchanges support broader transition pathways, such as low-carbon construction, industrial heat recovery, hazardous waste co-processing, or integrated bioeconomy development (Dong et al., 2017; Xue et al., 2022; Liao et al., 2024; Carissimi et al., 2024). In this context, regional IS analysis becomes part of transition planning.

Table 3. Regional scaling, network design, and governance insights from the corpus

Scale of analysis	Main lens or tool	Key insight for understanding IS/EIPs	Implication for policy or management	Ref.
Industrial park	Dynamic indicators	EIPs should be managed as evolving systems rather than static infrastructures	Monitoring systems need to track change, not only current performance	Felicio et al. (2016)
Urban system	Urban–industrial symbiosis assessment	Waste and industrial infrastructures can be co-designed for climate and resource benefits	City planning and industrial policy should be coordinated	Geng et al. (2010); Dong et al. (2014); Dong et al. (2017)
Regional network	Social network analysis	Network structure influences opportunity recognition, diffusion, and robustness	Facilitation should target central actors and weak links strategically	Vahidzadeh et al. (2021); Domini et al. (2025)
Emerging networks	Sustainability prospecting	Future networks may have uneven distributions of benefits and burdens	Early-stage appraisal should test who gains, who pays, and who bears risk	Martin & Harris (2018); Martin et al. (2015)
Regional planning	Infrastructure-capacity assessment	Technical potential is conditioned by logistics, treatment, and urban capacity	Potential mapping must be infrastructure-aware	Chertow et al. (2019)
Modeling and design	Sustainable IS modeling	Environmental desirability must be linked with implementable system design	Decision tools should integrate environmental and operational variables	Haq et al. (2021); Demartini et al. (2022)
Regional assessment frontier	Structural + environmental + regional integration	Benefits should be assessed across network structure and territorial metabolism together	Regional planning requires integrated, multi-scale metrics	Barrau et al. (2024)
EIP strategic governance	ESG + optimization framework	Environmental gaps, welfare issues, and community engagement can be assessed jointly with improvement portfolios	Future EIP management should connect assessment with action prioritization	Anelli et al. (2026)

7. Governance, implementation, and the rise of ESG

Implementation studies have long warned that industrial symbiosis is as much an organizational challenge as a technical one. Reviews of drivers and barriers emphasize information asymmetry, trust deficits, regulatory uncertainty, limited awareness, and coordination costs as recurrent obstacles to implementation (Rahman et al., 2016; Neves et al., 2019; Yeo et al., 2019; Demartini et al., 2022). This insight remains valid, but the attached corpus suggests that the governance conversation is evolving in two important ways.

The first shift is from barrier catalogues to outcome frameworks. Recent work increasingly asks what outcomes should be monitored and how governance should guide improvement, linking method choice to decision support rather than only diagnosis of failure (Wadström et al., 2021; Demartini et al., 2022).

The second shift is the emergence of ESG as a structuring language for EIP governance. The significance of the 2026 study by Anelli et al. is not just that it introduces another indicator set. Its real significance is that it reframes EIP assessment around a triadic governance logic in which environmental performance, social conditions, and governance quality are considered together, and in which assessment is linked to actionable improvement portfolios (Anelli et al., 2026). This is a notable departure from the dominant LCA-centric literature, which has historically treated environmental performance as the primary evaluative endpoint and social or governance factors as contextual variables rather than core performance domains.

Why does this matter? Because the conditions under which symbiosis is being promoted have changed. EIPs are increasingly asked to contribute to climate mitigation, resource security, local employment, community legitimacy, worker welfare, and strategic competitiveness all at once. In such a setting, environmental superiority alone may not guarantee political support or investment priority. A park that performs well on resource efficiency but poorly on community engagement or governance transparency may be less viable in the long run than one with slightly lower environmental gains but stronger institutional legitimacy. The ESG framing makes these trade-offs visible, even if operationalizing the social and governance dimensions remains more difficult than measuring emissions or material substitution.

Still, ESG should be integrated carefully. There is a risk that the concept becomes overly broad and dilutes the analytical strengths of industrial ecology. The attached literature suggests a more disciplined route. Environmental assessment should retain its methodological rigor through LCA, consequential analysis, and multi-level accounting; social assessment should focus on a bounded set of material issues such as welfare, health, participation, and distributional effects; and governance assessment should examine transparent decision rules, investment prioritization, inter-organizational coordination, and strategic monitoring (Felicio et al., 2016; Wadström et al., 2021; Kerdlap et al., 2024; Anelli et al., 2026). Under this interpretation, ESG becomes a governance wrapper around industrial ecology evidence, not a replacement for it.

8. Emerging frontier themes in the 2022–2026 literature

The newest studies in the corpus indicate several frontier directions that deserve particular attention. The first is multi-level integration. The UM3-LCE3-ISN framework is especially important because it extends earlier multi-level work by joining environmental and economic evaluation across entities, resource flows, and the wider network (Kerdlap et al., 2024). This matters because many real decisions in EIPs are taken neither at the abstract network level nor at the isolated firm level. They are taken in relation to particular exchanges whose impacts then aggregate unevenly across actors. Multi-level models are therefore a major step toward decision relevance.

A third frontier is the integration of optimization with environmental assessment. Studies on fly-ash utilization, iron and steel technologies, and ESG-governed EIPs suggest that the field is moving from simple impact comparison toward portfolio selection and budget-aware prioritization (Wang et al., 2022; Xue et al., 2022; Anelli et al., 2026). This shifts symbiosis closer to strategic operations and investment planning.

A fourth frontier is the increasingly explicit connection between symbiosis and resilient supply chains. Carissimi et al. (2024) do not focus only on IS, but their conclusions are highly relevant: localization, collaboration, digitization, and recycled raw materials can strengthen both sustainability and resilience. For IS research, this suggests that exchange networks should be assessed not only for resource efficiency, but also for their ability to stabilize supply, diversify sourcing, and reduce exposure to external shocks. The implication is that future reviews should examine resilience metrics alongside classic industrial ecology indicators.

A fifth frontier is the product-interface problem. Studies on EPDs and product-score divergence reveal that symbiotic products enter a contested communication space in which methodological inconsistency can hinder comparability (Durão et al., 2020; Konradsen et al., 2024). This is especially relevant for construction materials and other sectors where procurement decisions increasingly rely on declared environmental performance. IS research therefore needs stronger connections to product-category rules, declaration standards, and verification logic if it wants environmental gains to translate into market uptake.

A sixth frontier is the widening of acceptable host sectors and territorial configurations. Recent studies cover hazardous waste disposal in cement kilns, regional networks for waste minimization, steel slag in rubber compounds, bituminous pavements with paper and pulp residues, and cross-sector urban vertical farming synergies (Martin et al., 2022; Gobetti et al., 2024; Liao et al., 2024; Simões et al., 2024; Domini et al., 2025). These cases show that the field is no longer limited to classic heavy-industry exchanges. At the same time, this diversification raises the bar for comparison. Future synthesis must distinguish between high-volume structural symbioses and smaller niche valorization pathways, because their planning relevance differs.

Table 4. Emerging directions and unresolved questions in recent literature

Emerging theme	What recent studies add	Why it changes the field	Remaining challenge	Ref.
Multilevel network accounting	Joint environmental and economic evaluation across entity, flow, and network levels	Moves analysis closer to how managers and planners actually make decisions	High data demand and model complexity	Kerdlap et al. (2024)
Robust consequential analysis	Explicit treatment of marginal effects and uncertainty in cement symbiosis	Challenges overly static claims about benefit magnitude	Needs wider application beyond a few sectors	Lessard et al. (2024)
Optimization-based design	Hybrid LCA and portfolio selection under technical and economic constraints	Repositions IS as a strategic design problem	Requires reliable operational and cost data	Wang et al. (2022); Xue et al. (2022)
ESG-governed EIPs	Dual passive/active assessment with improvement portfolios	Expands evaluation beyond environmental metrics to welfare and governance	Social and governance indicators remain harder to standardize	Anelli et al. (2026)
Product comparability and declarations	Divergence across EPD/PCR rules for similar products	Shows that claimed benefits can be obscured at the market interface	Harmonization is still incomplete	Durão et al. (2020); Konradsen et al. (2024)
Regional structural assessment	Integration of structural, environmental, and territorial perspectives	Broadens IS from park logic to territorial metabolism	Technical potential may still exceed implementable potential	Barrau et al. (2024); Domini et al. (2025)
Circular supply-chain resilience	Stronger link between circular practices, collaboration, and resilience	Adds strategic value beyond emissions reduction	Resilience metrics are rarely embedded in IS assessment	Carissimi et al. (2024)
Expanded host sectors	New cases in hazardous waste co-processing, rubber, pavements, and urban farming	Demonstrates growing versatility of symbiosis applications	Need for better classification of scalable versus niche pathways	Martin et al. (2022); Gobetti et al. (2024); Liao et al. (2024); Simões et al. (2024)

9. Toward an updated interpretive framework

Drawing the strands together, the updated literature supports an interpretive framework in which industrial symbiosis and eco-industrial parks are understood through five linked dimensions: exchange logic, performance logic, network logic, governance logic, and transition logic.

The first dimension is exchange logic. This is the classic industrial ecology concern with what flows move between whom, in what form, and through which technical interface (Chertow, 2000; Zhang et al., 2015; Vahidzadeh & Bertanza, 2022). Without this layer, IS becomes a metaphor rather than an operational strategy.

The second dimension is performance logic. Here the literature demonstrates that credible evaluation depends on transparent baselines, well-specified boundaries, careful allocation, and, increasingly, uncertainty treatment and multi-level accounting (Mattila et al., 2010; Mattila et al., 2012; Aissani et al., 2019; Kerdlap et al., 2020a, 2020b; Kerdlap et al., 2024; Lessard et al., 2024; Ruini et al., 2025). This dimension guards the field against overstated circularity claims.

The third dimension is network logic. Symbiosis outcomes are shaped by the architecture of relations among actors, the density and centrality of exchange structures, and the infrastructural conditions that support material circulation at park and regional scales (Martin & Harris, 2018; Chertow et al., 2019; Vahidzadeh et al., 2021; Barrau et al., 2024; Domini et al., 2025). This dimension explains why technically plausible exchanges do not always materialize or endure.

The fourth dimension is governance logic. The field increasingly recognizes that information sharing, trust, coordination, decision rules, and strategic monitoring are not peripheral conditions but constitutive elements of symbiosis performance (Felicio et al., 2016; Rahman et al., 2016; Yeo et al., 2019; Wadström et al., 2021; Demartini et al., 2022; Anelli et al., 2026). This is where ESG enters most naturally: as a governance architecture that broadens the evaluative horizon while keeping action orientation.

The fifth dimension is transition logic. Recent studies suggest that IS should be understood as part of wider decarbonization, circular supply-chain, and territorial transition pathways rather than as isolated exchange optimization (Xue et al., 2022; Carissimi et al., 2024; Liao et al., 2024; Anelli et al., 2026). This dimension connects the literature to industrial strategy and climate policy.

This framework also clarifies why familiar debates persist. Allocation disputes are methodological, but also governance questions about who receives credit. Transport disputes are logistical, but also issues of regional structure. ESG is not a departure from industrial ecology; it reflects broader demands for legitimacy and action-oriented governance.

10. Research agenda for the next generation of review and empirical work

Several priorities emerge clearly from the attached corpus. First, future research should standardize minimum reporting requirements for IS and EIP assessment. At a minimum, studies should state the reference scenario, substitution logic, transport assumptions, allocation rule, scale of analysis, and major uncertainty sources in a way that permits cross-study interpretation (Mattila et al., 2012; Aissani et al., 2019; Kerdlap et al., 2020a, 2020b; Lessard et al., 2024; Ruini et al., 2025). Without this, the literature will continue to accumulate cases faster than it accumulates comparability.

Second, more studies should connect environmental assessment with economic feasibility and implementation constraints. The newer integrated models provide a promising basis, but they are still relatively rare compared with the large body of environmental case studies (Kerdlap et al., 2024; Wang et al., 2022; Xue et al., 2022). Top-tier work should therefore aim for assessment architectures that are environmentally rigorous, financially interpretable, and operationally actionable.

Third, research should do more to distinguish structural symbiosis from niche valorization. Some exchanges fundamentally reshape industrial metabolism because they involve high-volume flows and infrastructural lock-in, whereas others provide useful but limited incremental gains. Both are valuable, but they should not be discussed as if they have the same transition significance (Ammenberg et al., 2015; Capucha et al., 2023; Martin et al., 2022; Gobetti et al., 2024; Simões et al., 2024). A stronger typology of scaling relevance would make future reviews more analytically precise.

Fourth, the social and governance dimensions of EIPs should be operationalized more rigorously. The ESG-oriented literature is promising, but still nascent in the attached corpus. Future work should develop indicators and evaluation protocols for distributional effects, worker welfare, community relations, coordination quality, and strategic transparency that are robust enough to complement environmental assessment without collapsing into generic sustainability rhetoric (Wadström et al., 2021; Demartini et al., 2022; Anelli et al., 2026).

Fifth, regional and territorial perspectives should be expanded. The literature increasingly shows that some of the most relevant opportunities lie beyond the fence line of individual parks. Yet regional studies still face a gap between technical potential and implementable potential. More work is needed on infrastructure-aware screening, actor coordination mechanisms, and regional governance design so that symbiosis can be embedded in territorial planning rather than treated as a set of opportunistic bilateral exchanges (Chertow et al., 2019; Vahidzadeh et al., 2021; Barrau et al., 2024; Domini et al., 2025).

Finally, review scholarship itself should move beyond case accumulation toward explicit comparison of methodological architectures and governance implications.

11. CONCLUSION

The attached literature shows a field that has matured substantially. Industrial symbiosis and eco-industrial parks are no longer discussed only as inspiring examples of circularity; they are increasingly treated as measurable, designable, governable, and strategically prioritizable systems. The evidence base strongly supports the claim that symbiosis can reduce environmental burdens across multiple sectors, especially in cement, construction, steel, waste management, forest products, and integrated bio-based systems (Hashimoto et al., 2010; Sokka et al., 2011; Eckelman & Chertow, 2013; Yu et al., 2015; Wang et al., 2019; Xue et al., 2022; Capucha et al., 2023). At the same time, the review also shows why the field can no longer rely on generic benefit claims. Outcomes depend on baselines, allocation, transport, scale, and market assumptions, while implementation depends on network structure, governance capacity, and infrastructural context (Martin et al., 2015; Aissani et al., 2019; Chertow et al., 2019; Vahidzadeh et al., 2021; Lessard et al., 2024; Ruini et al., 2025).

The major substantive update revealed by the recent literature is the shift toward integration. Environmental assessment is increasingly linked with costing, optimization, network analysis, supply-chain resilience, regional planning, and ESG governance (Demartini et al., 2022; Wang et al., 2022; Carissimi et al., 2024; Kerdlap et al., 2024; Barrau et al., 2024; Anelli et al., 2026). Industrial symbiosis is therefore no longer simply about closing loops, but about making those loops analytically defensible, strategically useful, and socially legitimate.

The most important conclusion is therefore not simply that industrial symbiosis works, but that it works best when treated as transition infrastructure: rigorously evaluated, network-aware, regionally embedded, and governed through transparent, multi-dimensional decision frameworks.

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